newsletter

OF THE JAMES CLERK MAXWELL FOUNDATION, EDINBURGH

Issue No.11 *Summer 2018*

ISSN 2058-7503 (Print)
ISSN 2058-7511 (Online)

Wireless Advances using Visible Light (LiFi)

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Introduction

Whether using smartphones or computers, wireless networks allow us to watch videos and communicate with others by email, Facebook or Instagram even while on the move.

Existing technology uses wireless cellular communication and WiFi (Wireless-Fidelity). It uses the radio band (RF) of the electromagnetic spectrum (Figure 1).

This article looks at existing technology [1] and then at the emerging technology of Visible Light Communication (VLC) known as LiFi (Light-Fidelity). LiFi uses the visible band and Figure 1 shows that the frequencies under LiFi are much higher (and wavelengths correspondingly shorter) than under cellular communication or WiFi.

Band	Wavelength	Frequency
Gamma-ray	<0.01 nm	>30 EHz
X-ray	0.01-10 nm	30 PHz-30 EHz
Ultraviolet	10 nm-400 nm	790 THz-30 PHz
Visible (VLC)	400 nm-750 nm	405 THz-790 THz
Infrared	750 nm-1 mm	300 GHz-405 THz
Radio (RF)	>1 mm	3 Hz- 300 GHz

Figure 1[2]: The electromagnetic spectrum divided into bands

Cellular communication

Figure 2: A 'macro-cell' base-station

Five billion people worldwide own mobile phones with some two billion of these being smartphones. Smartphones offer internet access via wireless cellular communication. When on the move (e.g. using mobile phones in a car or a train), wireless communication systems are used.
In addition, almost two billion sensors (e.g. smart-meters and sensors on autonomous vehicles) are connected to the internet.

These networks have necessitated the deployment of more than three million base-stations (radio masts) world-wide.

A cellular base-station, in a rural setting, uses 'macro-cells' (Figure 2) which serve users situated within a radius of about a ten to twenty kilometres. Base-stations are used to support voice and data communication traffic to and from personal devices.

Figure 3: A 'micro-cell' base-station (which appears like another street lamp)

In an urban setting, where user density is higher, smaller cells ('micro-cells') are typically used. Figure 3 shows a pavement mounted transmitter plus the associated cabinet.
These micro-cells enable individual handsets to reach data-transfer-rates, in 4G systems, of up to 15-20 Mbit/s (million bits of data – ones and zeros – per second). Through advances in technology, this data-transfer-rate is predicted to reach 40 Mbit/s by 2021.

International agreement provides for the allocation of specific parts of the electromagnetic spectrum for carrying voice and data traffic. These networks, through a system of licences, exploit Maxwell's electromagnetic waves in the RF part of the spectrum.

Claude Shannon's seminal work in information theory [3], shows that the capacity or data-transfer-rate achievable in a wireless link (or network) is directly proportional to the bandwidth [4] of the transmitted signal.

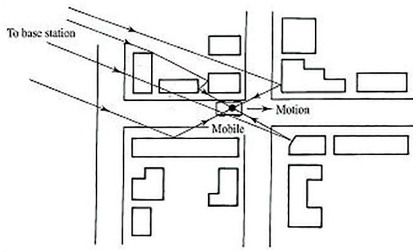

Figure 4: Multiple propagation paths occur where signals are reflected off buildings (courtesy of the Pearson Education[5])

Mobile communications suffer from multiple propagation paths as and when the signal (between the transmitter and receiver) is reflected off nearby buildings (Figure 4). At the receiving antenna, these various reflected signals are simply summed (algebraically) at the operating carrier frequency. This results in both constructive and disruptive summation, the latter resulting in a signal loss – known as a *'deep fade'*. In order to counteract such signal loss, significant channel-modelling software and digital-signal-processing algorithms require to be employed in the receiver.

1 I. A. Glover and P.M. Grant, "Digital Communications", Pearson Education, 3rd edition, 2013.
2 Millimetre(mm)=10^{-3} metres : Nanometre(nm)=10^{-9} metres : Megahertz(MHz)=10^{6} Hertz : Gigahertz(GHz)=10^{9} Hertz : Terrahertz(THz)=10^{12} Hertz : Picohertz(PHz)=10^{15} Hertz : Exahertz(EHz)=10^{18} Hertz
3 C.E. Shannon, "A Mathematical Theory of Communication", Bell System Technical Journal, Vol. 21, pp. 379-432 and 623-656, 1948.
4 Signal bandwidth, in Hz, depends on transmitted data-transfer-rate and type of modulation and is measured by conducting Fourier analysis.
5 See footnote 1

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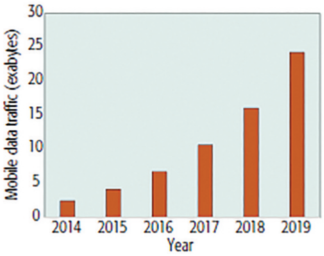

Figure 5: Growth in worldwide mobile data traffic in exabytes (10^{16} bytes -8 bits - or data words) per month (courtesy of the IEEE)

Mobile data traffic (Figure 5) is increasing rapidly, due predominantly to video traffic (TV, YouTube, games, social media). This now accounts for more than 60% of the overall data traffic. Smartphones and tablet computers currently handle this demand, by off-loading, where possible, this dense traffic onto fixed WiFi networks, in order to exploit the higher data-transfer-rate capability of the latter. Mobile data traffic is predicted to grow by about 75% of current levels by 2021.

The radio band (RF) below 10 GHz

As the increasing number of smartphone users has resulted in an exponentially increasing demand for outdoor wireless communication, the available radio frequency band below 10 GHz (where current transmissions are located) has become increasingly overcrowded. The wireless communication industry has responded to this challenge in two ways.

The first way is to use higher frequencies (i.e. above 10 GHz) to achieve *'millimetre-wave'* communication. However, these higher frequencies imply a higher propagation-path signal loss which requires either (i) even smaller cells or (ii) higher transmitter output power from both the base-station and the mobile handset. Both of these requirements are more difficult to implement at higher frequencies. Thus, higher frequency systems must be designed to enhance the probability of achieving a (multipath-free) strong line-of-sight (LoS) propagation path. Here beam-forming techniques are attractive to focus (or beam) the transmitted signals towards certain users.

The second approach is to use very small cells having only about a fifty metre radius from the base-station. Reducing cell size has been the major contributor for enhancing system performance in current cellular communications. However, a disadvantage is that providing the supporting infrastructure (for very small cells) requires more base-stations and a much more sophisticated fibre optic *'backhaul'*.

Figure 6: Example of a domestic WiFi router

WiFi communication

In a world population of almost eight billion people, homes and businesses have billions of connections for fixed internet access though WiFi (Wireless-Fidelity).

The WiFi access point or router (Figure 6) connects to the internet via the home or the office telephone system or the internal office network (Ethernet) in order to facilitate wireless data traffic to and from the computer (or other connected devices).

WiFi (unlike cellular communication) does not provide the capability of communicating with faster moving users, such as pedestrians or users in cars, but WiFi does support higher data-transfer-rates than cellular communications (typically 50-70 Mbit/s as against 15-20 Mbit/s).

WiFi uses an internationally agreed radio frequency band around 2.4 GHz (called the *'Industrial, Scientific and Medical'* (ISM) band). Users listen for local-user transmissions to permit them to share the frequency resource. They transmit and receive *'packetised'* data traffic to and from the router as and when the local ISM band is free of data traffic.

Origins of VLC

Current research is extending communication beyond the radio band (RF) to use the visible band (*'Visible Light Communication'* – VLC) i.e. using visible light rather than the cluttered, scarce, expensive and lower frequency radio band.

VLC has its origins in Alexander Graham Bell's[6] photophone (1880) which used a beam of light to send messages. Unfortunately, this early discovery was eclipsed by the subsequent discovery of radio communication by Marconi and others.

More than a century later, wireless communication, using light in the infrared band (Figure 1), is widely used in remote controls for TVs but the data-transfer-rate is extremely low.

LiFi (VLC) communication

VLC technology (in comparison with radio technology) provides for higher data-transfer-rates and additional system capacity. It provides energy-efficient indoor lighting while, at the same time, transmitting a large amount of indoor data traffic.

VLC is not regulated, thereby significantly reducing the costs for operators. VLC presents a viable alternative to traditional wireless communication.

It was Professor Harald Haas[7] of the University of Edinburgh who first called VLC signals, "LiFi" (Light-Fidelity). The seminal presentation of Professor Harald Haas, at the 2011 annual interdisciplinary *'TED Conference',* ushered in the start of serious LiFi developments around the world. In addition to winning several recent *'best-paper'* awards, Professor Haas has been reported many times on radio and TV in the last seven years. He has been recognised for his pioneering advances in LiFi and is now known internationally as the *"father of LiFi"*.

Implementation of Li-Fi using LEDs

Figure 7: The LED LiFi (VLC) concept – note the ceiling LEDs using light to transmit data (courtesy of the IEEE)

The initial breakthrough was the demonstration that, with off-the-shelf Light Emitting Diodes (LEDs), VLC could achieve high data-transfer-rates, much faster than WiFi. Advanced single link data transmissions (using a gallium nitride source) achieved data-transfer-rates of up to 8 Gbit/s and up to 15 Gbit/s from a blue laser transmitter.

Thus, the most important implementation of high speed Li-Fi technology was to use LEDs to transmit data at the same time as they illuminated a room (Figure 7). By embedding an electronic chip into LED bulbs, a large volume of data could be streamed using light – whether in the visible, infrared or ultraviolet band.

6 A.G. Bell, "The Photophone", Science, Vol. 1, No. 11, pp. 130-131, 1880.
7 S. Dimitrov and H. Haas, "Principles of LED Light Communications: Towards Networked Li-Fi". Cambridge University Press, 2015.

High brightness white LED bulbs (luminaries) now exceed 200 lumens per watt with an efficiency and life expectancy exceeding that of either incandescent or fluorescent products. A 5-watt LED produces as much light as a 60-watt incandescent bulb.

There is now widespread deployment of LED bulbs (luminaries) in our homes, offices and in our streetlights. It was predicted in a McKinsey & Company report (in 2011) that, by 2020, 70% of residential and 90% of architectural lighting will be LED based. Thus, modern lighting infrastructure will increasingly be also used for LiFi deployment.

The cheapest, and most common, LED is a *'blue LED'* which is coated with a yellow phosphor to ensure that it actually emits broad-spectrum white light. As the LED is a semiconductor, an LED can be *'intensity-modulated'*. Such an LED can be switched 'on' and 'off' at a very fast rate so that, to the user, the light appears to be permanently 'on' but the electronic receiver detects the ('on' and 'off') data transmissions. Typical switching times are down to tens of nanoseconds which is too fast to be detected by the eye.

Thus, the most widely used single-carrier LiFi modulation scheme was simple 'on' and 'off' keying of the LED. This provided a good trade-off between system performance and implementation complexity and supported dimming of the lighting (without reducing the LiFi data-transfer-rate). The (intensity-modulated) signal was detected in the receiver with a normal photodiode (with avalanche photodiodes being deployed for the higher rate transmissions).

Electromagnetic waves in the visible band cannot penetrate through most surfaces that are present in everyday surroundings. LiFi transmissions are localised eliminating the possibility of casual eavesdropping. This provides for more private (although not cryptographically secure) communications. This is attractive for achieving confidentiality e.g. for financial sector communications. Radio waves, on the other hand, are particularly adept at providing connectivity through walls and most commonly used building materials.

The fact that LEDs are natural beam-formers enables local containment of LiFi signals. LiFi has been conceived predominantly as a point-to-point data communication (or cable replacement) technique.

Also, if one counts in units of 1 Hz, the number of frequencies in the visible band (assuming LEDs were readily available to generate all the required different colours of light) exceeds by a multiple of over a million the number of frequencies available in the radio band.

In a practical deployment using LiFi, an order of magnitude increase in the data-transfer-rate can reasonably be expected; some 1 Gbit/s under LiFi as opposed to 20 Mbit/s under cellular and 70 Mbit/s under WiFi.

Maxwell's 1855 Colour Triangle

In addition to using white LEDs, a modern development of Maxwell's 1855 colour triangle can be used. This enables transmitters to simultaneously exploit the various colours in the visible spectrum (red, green, blue etc.) and thereby effect parallel transmission links operating at different frequencies (Figures 8 and 9).

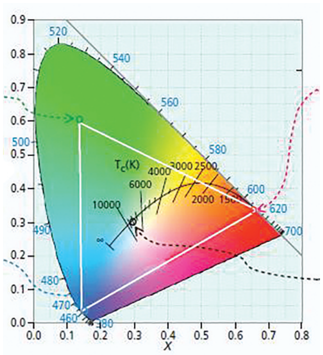

Figure 8: By showing the chromaticity values (according to the x-axis and y-axis values) on the chromaticity diagram (Commission Internationale de l'Eclairage – CIE 1931), this Figure shows how to use LEDs with three different colours for parallel LiFi (VLC) transmissions (courtesy of the IEEE)

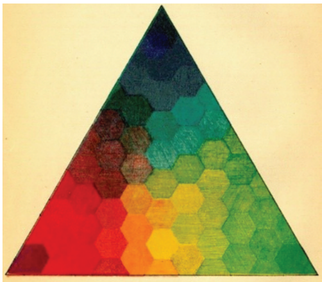

Figure 9: Maxwell's colour triangle (if rotated corresponds to the white triangle shown in Figure 8)

Advantages of VLC

Recent studies indicate that a substantial portion (greater than 70%) of wireless traffic originates indoors.

In addition to what has been said above, VLC offers other advantages as compared to RF transmissions.

VLC (by *'piggy backing'* on existing lighting units) is almost free as most indoor environments are illuminated.

VLC requires minimal additional energy in order to operate the necessary circuitry. As it is low power and safe, LiFi can further be viewed as an environmentally green technology.

As VLC relies on intensity modulation, the receiver (an *'incoherent'* receiver) is simpler and cheaper than the type of receiver used for RF systems (a *'coherent'* receiver, which requires frequency and phase information).

As the wavelength of VLC is much smaller (400-750 nm – Figure 1) than the typical dimensions of a photodetector, this effectively removes the *'multipath-fading'* experienced in RF systems. This occurs because the VLC channel does not exhibit *'Doppler spread'* (because multipath interference occurs on the micron[8] scale and this is all averaged in the photodiode receiver). Thus, in comparison with RF communication systems, VLC does not require sophisticated receiver channel tracking algorithms.

As VLC signals do not interfere with the operation of sensitive electronic systems, they can be used in a variety of applications where RF transmissions are not allowed (e.g. hospitals, aircraft or chemical plants). Also, VLC provides the potential for films to be watched through lamplight at home and for deep-sea diver communications.

The key to a high-performing VLC system is not only the increase in the spectral efficiency and transmission performance (bit/sec per Hz of available bandwidth). For mobile systems, it is the *'area-spectral-efficiency'* i.e. the mobile data-transfer-rates that can be offered to all users in a cell. In this context, VLC has been shown to be able to provide at least an order of magnitude improvement in *'area-spectral-efficiency'* (over RF).

8 Micron=10^{-6} metres=1000 nm

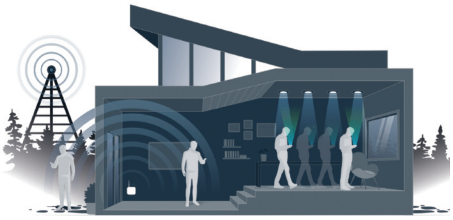

Figure 10: Seamless interlinking between cellular, WiFi and LiFi systems (courtesy pureLiFi Ltd).

LiFi now includes bi-directional multi-user communication, i.e. point-to-multi-point and multi-point-to-point communication. LiFi also permits multiple access points to form a wireless network of very small (optical) cells, with seamless handover (Figure 10). This means that LiFi can provide full user mobility.

There is considerable effort being dedicated to developing LED based communication for intelligent transportation systems and for enhancing vehicle safety e.g. transmission via traffic lights, via vehicle brake lights and via vehicle-to-vehicle communications.

Disadvantages of VLC

As the data-transfer-rate increases in LiFi networks to above 0.5 Gbit/s, single carrier modulation schemes (such as 'on' and 'off' keying) start to suffer from unwanted effects. Thus, LiFi implementations now use a much more sophisticated modulation technique which is known, in RF communications, as *'Orthogonal Frequency-Division Multiplexing'* (OFDM). Here data is routed into a serial-to-parallel converter before being transmitted as many (lower data-transfer-rate) parallel channels on subcarrier frequencies.

Such OFDM multi-carrier modulation is now deployed in LiFi to extend the data-transfer-rate from 0.5 Gbits/s up to and beyond 1 Gbit/s, with the many parallel data streams being transmitted simultaneously through a collection of these (orthogonal) subcarriers.

However, VLC is not expected to replace RF for long range, non-line-of-sight, outdoor links. Thus VLC and RF are thus seen as *complementary* rather than *competing* technologies.

VLC also a low data-transfer-rate transmitter

Although this article has concentrated on the high data-transfer-rate obtainable under VLC, a potential low data-transfer-rate application is available for sensors determining indoor location. This arises because the accuracy of VLC systems for location detection is of the order of tens of centimetres, compared to ten metres for the (RF based) Global Positioning Systems – GPS.

Figure 11: Use of a Smartphone for indoor position location (courtesy of the IEEE and Qualcomm)

VLC positioning can be achieved with very minimal alteration to existing lighting installations. A single photodiode receiver can be replaced with a two-dimensional image sensor array, as incorporated in smartphone cameras (Figure 11). This sensor uses *'angle-of-arrival'* estimation to determine a user position with respect the overhead light fixtures. The data-transfer-rate, needed for such sensors, are slow – only Kbit/s.

Sensor arrays further offer the ability to spatially separate out multiple transmission sources. They have the potential, if used outdoors, to remove interference from sunlight and streetlights.

Indoor location is of special interest to retail and other operators for product search and targeted advertising. This market is predicted to reach $5 billion by 2018.

Commercialisation of LiFi

Within the UK there are major inter-university partnerships investigating *'Ultra-parallel Visible Light Communication'* and, together with ten industrial partners, developing VLC techniques.

Worldwide, VLC has seen a recent explosion in awarded patents. There were virtually no filings in 2002 but, ten years later, there were almost 200 annual applications filed, predominantly by Korean and Japanese investigators.

Figure 12: LED luminary link for data-transfer-rates of 1 Gbit/s over 4 metres (courtesy Fraunhofer-Hertz Institute, Berlin)

One VLC product, produced by the Fraunhofer-Hertz[9] Institute in Berlin, provides data-transfer-rates of up to 1 Gbit/s over a 4 metre range (Figure 12).

There are today many major electronics companies who have developed VLC products e.g. a desktop lamp, a USB stick and a LED panel. A major lighting company has recently added a LiFi-enabled LED to its office lighting portfolio.

One of the most active and pioneering companies in developing networked LiFi products (offering *'mobility'* and *'hand-over'* as in cellular systems) is pureLiFi, the fifty person Edinburgh start-up formed by Professor Haas' Edinburgh research group.

They launched Li-Flame in 2015, a fully networked LiFi transceiver with multiuser access and handover. In 2016, they launched LiFi-X the world's first LiFi dongle with a 40 Mbit/s data-transfer-rate.

Figure 13 : A modem/dongle fully integrated into a laptop (courtesy of pureLiFi)

Their current bidirectional unit includes an access point providing secure networked communications and which is compatible with the Windows, Linux and MacOS operating systems (Figure 13). PureLiFi recently concluded an agreement to further develop LiFi applications for the Asian market.

Conclusion

LiFi is a new and fast developing communications technology of enormous potential. It offers very exciting opportunities to complement cellular communication systems and WiFi systems. LiFi meets customer demand for ever faster data-transfer-rates.

9 Heinrich Hertz, by providing the first practical demonstration of electromagnetic signals, showed that *"Maestro Maxwell was right"*.

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